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STATE OF THE ART IN FIBER OPTICS COMMUNICATIONS AND DATA TRANSF--ETC(U)
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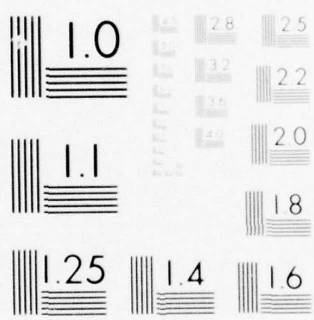

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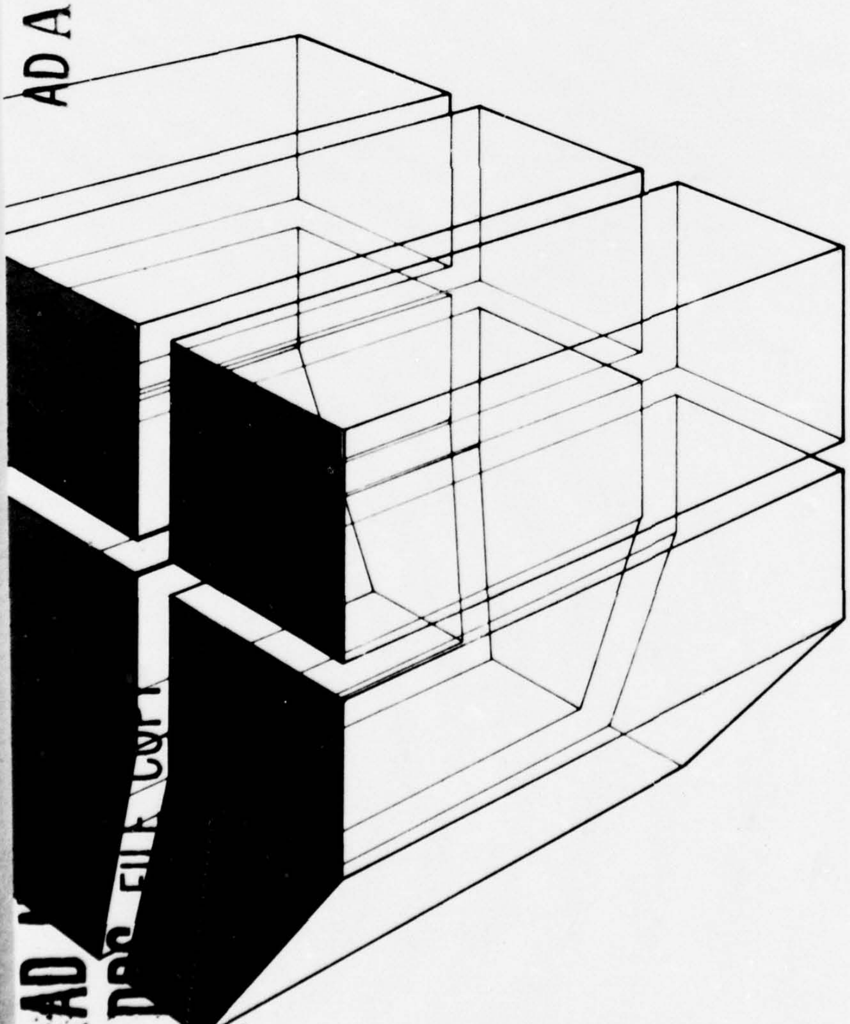
INTERIM REPORT E-111
July 1977
EMI Circumvention by Fiber Optic Transmission

STATE OF THE ART IN FIBER OPTICS COMMUNICATIONS AND DATA TRANSFER

by
R. G. McCormack
W. J. Croisant
P. C. Lam



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This report addresses the state of the art of fiber optic communications as related to U. S. Army Corps of Engineers military construction. It discusses the general capabilities of commercially available fiber optics and summarizes the research and development work being done in the area by other Department of Defense and U. S. Government agencies. Potential Corps of Engineers usage of fiber optics is discussed, and nuclear radiation hardening aspects are summarized. Interfacing optical fibers with electronics is discussed along with factors which limit the performance of fiber optics data transmission links.

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FOREWORD

This research was conducted for the Directorate of Military Construction, Office of the Chief of Engineers (OCE) under Project 4A762719AT40, "Mobility, Soils, and Weapons Effects"; Technical Area A1, "Weapons Effects and Protective Structures"; Work Unit 022, "EMI Circumvention of Fiber Optic Transmission." The applicable QCR is 1.03.010. The OCE Technical Monitor was Mr. H. McCauley, DAEN-MCE-D.

The study was conducted by the Electrical-Mechanical Branch (EPM), Energy and Power Division (EP), U. S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. The CERL Principal Investigator was Mr. R. G. McCormack.

Appreciation is expressed to D. C. Sieber and M. J. Pollock of CERL and J. Verdeyen of the University of Illinois at Urbana-Champaign for their contributions.

COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director. Mr. R. G. Donaghy is Chief of EP and Mr. M. J. Pollock is Chief of EPM.

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1 INTRODUCTION

Background

In recent years, communications-related engineering has devoted considerable effort to information transmission media. The increased use of computers requires broadband data links to meet the demand for high-speed data handling. Coordination of today's more complex, highly integrated military operations places greater demands on the communications systems used. As technology has grown in military weapon control system facilities, automated monitoring and controlling of all aspects of the facilities' operation have been developed. The Corps of Engineers has an expanding need for improved methods of data and information handling in this and similar facility construction areas.

Alternatives available for broadband communications links are limited, and some links considered broadband in the past will be inadequate for future needs. An alternative which has been extensively investigated in recent years is the use of light in optical communications links. Although development of the laser has expanded possiblities for optical communications, atmospheric optical links are weather-dependent and therefore unreliable except for short-range links. The optical fiber is a means of guiding a light signal and circumventing dependence on weather and line of sight.

Fiber optics are currently being studied by a variety of military communications applications. The U. S. Army Electronics Command is investigating fiber optics from an overall communications standpoint for military operations, and the Navy and Air Force are investigating airborne and shipboard applications of optical fibers. Use of fiber optics for undersea cables, satellite and spaceship applications, battlefield applications, electromagnetic pulse (EMP) circumvention, and many other applications is also being examined.

As part of the overall investigation of fiber optics military communications applications, the U. S. Army Construction Engineering Research Laboratory (CERL) is studying specific problems related to Corps of Engineers military construction applications, such as the relaying of facility monitor and control information in EMP-hardened facilities, storage and handling areas for explosives and highly flammable materials, and areas of intense electromagnetic interference. To begin this research, an assessment of the capabilities and near-term expected advancements in fiber optics technology is needed.

Objective

The objective of this study was to summarize the current state of the art in fiber optics. The summary was to show capabilities of currently available fibers and related components and to examine predicted near-term usage of fiber optics data links by assessing current research and development.

Approach

A three-step approach was used in assessing the state of the art in fiber optics.

1. A literature search was conducted.

2. Other Government agency work was surveyed.

3. Summaries of research, development, and available products were obtained from fiber optics manufacturers.

The literature search involved automated searches of Defense Documentation Center (DDC) reports, National Technical Information Service (NTIS) reports, and papers (primarily from journals) listed in the Engineering Index.* In addition, reports from the Fiber Optic Information Exchange Library Program sponsored by the Naval Electronics Laboratory Center were requested, and recent journals were scanned. Reading and summarizing the tremendous number of reports, articles, and papers dealing with fiber optics was impossible, but the reference list at the end of the report, although it is by no means a complete listing, should assist the reader in obtaining additional information.

Other Government agency work was surveyed primarily by an automated work unit summary provided by DDC, which includes only Department of Defense (DOD) sponsored research and development (R&D). Some non-DOD Government research was summarized

*The search of Engineering Index listed papers was performed by the System Development Corporation International Search Service. Because of the large number of references related to fiber optics (708), only those relating to fiber optics communications are included in the reference list at the end of the report.

by surveying periodicals, but the listings in this area are not complete. Some assistance in summarizing R&D efforts was obtained through telephone contacts and by a visit to the Naval Electronics Laboratory Center.

Letters requesting information on available fiber optics hardware were sent to manufacturers. Appendix A summarizes the information obtained. Some manufacturers provided additional information concerning R&D which they are currently performing.

Scope

This report is intended to provide a summary of the state of the art in fiber optics communications as related to Army Corps of Engineers military construction applications. It is written to provide general information to those who may not be knowledgeable in this technological area and is therefore not a highly technical document. It is primarily directed toward data transmission applications and does not include applications in image transfer, displays, fiber scopes, inspection devices, special-purpose lighting, etc.

2 DISCUSSION OF FIBER OPTICS STATE OF THE ART

Principles of Fiber Optics Operation

Fiber optic theory is based on transmission of light by a small threadlike glass or plastic fiber which uses the principle of total internal reflection, or total confinement of all light propagating in the fiber. Fibers are fabricated in two different ways, which result in two different fiber types: the step-index and graded-index fibers.

The step-index fiber is fabricated with two distinct materials as the fiber core and cladding; the cladding's index of refraction is lower than that of the core. The fibers are made so that intimate contact exists between the core and cladding.

When a light ray propagates through a transparent material and reaches a boundary with a material having a different index of refraction, the light ray is bent, as illustrated in Figure 1. If the second material's index of refraction is lower than that of the first material, the incident angle θ is greater than the angle ϕ. In other words, the light ray is bent toward the dielectric interface. If the incident angle θ is made smaller, as illustrated in the figure, a critical angle at which the ray will be bent parallel to the interface is reached. At angles smaller than the critical angle, the rays will be reflected from the interface. Thus, if the dielectric interface is the interface between the core and cladding of an optical fiber, all light propagating in the fiber core will be totally internally reflected if all internal rays are incident at angles less than the critical angle.

The critical angle for total internal reflection in the fiber is further related to a maximum acceptance angle for light incident on the end of the fiber. As shown in

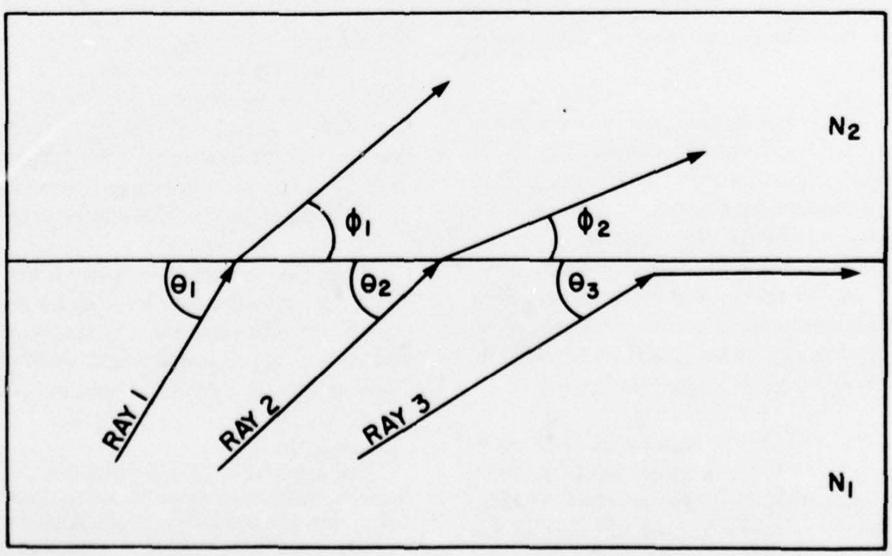

Figure 1. Light ray bending at a dielectric interface.

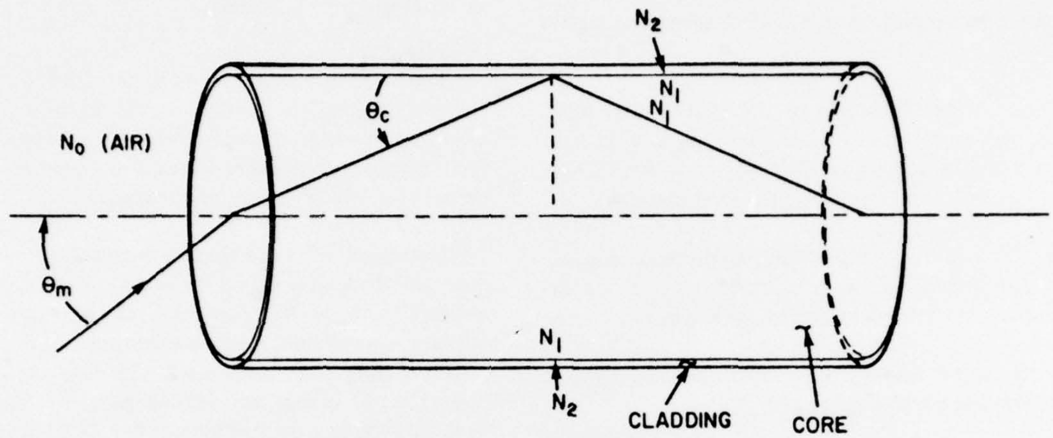

Figure 2. Ray entering the end of a fiber.

Figure 2, light incident on the fiber end of angle θ_m is refracted away from the air-fiber interface at an angle θ_c relative to the core-cladding interface. A maximum angle exists under which all internal rays will be incident on the core-cladding interface at less than the critical angle. This maximum angle is defined by the relationship

$$\sin \theta_m = \frac{1}{N_0} (N_1^2 - N_2^2)^{1/2} \qquad \text{[Eq 1]}$$

where θ_m = maximum acceptance angle

N_0 = index of refraction of exterior medium at fiber end

N_1 = index of refraction of the fiber core

N_2 = index of refraction of the fiber cladding.

If the exterior medium is air, then N_0 equals 1 and sin θ_m has been defined as the Numerical Aperture (NA) of the fiber. The NA is an important parameter in fiber design, since it is related to efficiency of coupling light into the fiber.

The NAs of currently available fibers vary from about 0.10 to nearly 0.66. Actually, fibers have been made using a fused silica core with an index of refraction of 1.457 and a doped silica cladding with an index of 1.456, yielding an NA of 0.05 and a resultant acceptance angle of 2.9 degrees. The NA of 0.66, however, gives an acceptance angle of 41.3 degrees, which makes coupling light into the fiber easier. Thus, the acceptance angle and core diameter determine the ease with which light is coupled into the filter.

In the graded-index or self-focusing filter, instead of two distinctively separate materials for core and cladding, a dopant material is diffused into the fiber from the outside; the index of refraction thus varies with radial location in the fiber. In this fiber, the propagating rays are gradually, rather than suddenly, bent back toward the fiber axis.

Graded-index fibers are manufactured using an ion exchange method to establish the varying index of refraction. One method of manufacture is to dip the glass fiber in molten salt at a high temperature; during this process, ions in the fiber are replaced by those of the salt bath through thermal diffusion. The magnitude of ion exchange varies with radius, and thus a graded-index of refraction is developed in the fiber. Due to the gradual change in index of refraction, the fiber does not rely on total internal reflection for light propagation, but instead acts as a lens and focuses the light rays to the center of the fiber.

Graded-index manufacturers claim several advantages, including the following:

1. Due to the focusing action of the graded-index fiber, fewer modes propagate than in a step-index

multimode fiber,* and thus less pulse spreading and greater bandwidth can be attained. (This property is discussed more fully in the **Optical Fiber Parameters** section.)

2. The focusing action of the graded-index fiber also allows it to be used to transmit images. With step-index fibers, coherent bundles of hundreds of fibers must be used to transmit a single picture element.

3. The potential for reducing attenuation is good, since the attenuation due to scattering from imperfections at the core-clad interface is eliminated.

4. In short lengths, the polarization of light is maintained to a high degree.

Types of Optical Fibers

Fibers are manufactured in a variety of configurations for different applications. Categories by which fibers can be classified, in addition to the step-index vs graded-index classification discussed in the previous section, include:

1. Material type
2. High loss vs low loss
3. Single-mode vs multimode
4. Single fiber vs bundles.

Material Type

Some of the materials used are glass (including quartz), plastic, and combinations thereof, in addition to various dopants to alter the index of refraction. Fibers having a glass sleeve with gas or liquid core have been made, but are not commercially available.

Pure fused silica (SiO_2) is a common material for low-loss fibers. It is one of the few materials which can solidify in the molten state and remain in the amorphous (noncrystalline) state. Its melting point of 1723°C makes it very difficult to work with. The addition of soda (Na_2O) lowers the melting point but does not make a durable glass. Addition of lime (CaO, usually in the form of limestone $CaCO_3$) as well, however, adds strength and provides a durable glass. This soda-lime glass used in making optical fibers is also the material commonly used in bottles, drinking glasses, windows, etc.

Boron (in the form of B_2O_3) is among the various dopants used to alter the index of refraction of glass. Adding boron to silica results in a glass of low thermal expansion; this glass is commonly used in making heat-resistant items such as ovenware. Borosilicate glass has an index of refraction ranging from 1.455 to 1.462 depending on the amount of dopant used. Since the boron atom nucleus has a large cross section* to neutron radiations, fibers using this material have a low degree of hardness for nuclear environments.

Lead (in the form of PbO), another dopant used, yields a high index of refraction ranging upward from 1.6, depending on overall composition. It is therefore sometimes used in the core of optical fibers when a high NA is desired. Lead-doped silica, however, has higher attenuation than boron-doped silica due to higher scattering losses. In addition, lead-silicate fibers are susceptible to ionizing nuclear radiation.

Quartz, which is the crystalline form of silica, has seen some usage in optical fibers. The index of refraction of fused quartz ranges from 1.425 to 1.456. Commercial-grade fused quartz, such as Optosil I and Homosil manufactured by Amersil, Inc., is available for making optical fibers. However, fused silica is usually preferred over fused quartz in fabricating low-loss

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*Light energy propagates in an optical fiber in exactly the same manner that radio frequency (RF) energy propagates in a metallic waveguide. In multimode fibers, however, the wavelength of the propagating light is normally much less than the diameter of the fiber. In order for energy to propagate in a waveguide, components of both the electric and magnetic fields must be perpendicular to the direction of propagation. This condition can be achieved with many different field patterns within the waveguide. These different field patterns are called modes.

In general, there are two kinds of modes. In one kind, the electric field is always predominantly transverse to the direction of propagation; this type of mode is called transverse electric (TE). In the other kind, called transverse magnetic (TM), the magnetic field vector is predominantly transverse to the direction of propagation. Mode orders are designated by the number of half-wavelength variations of the transverse field component which exist across the waveguide dimension.

Each propagating mode has a cutoff wavelength (the wavelength at which attenuation sharply increases) determined by the waveguide dimensions. Many modes will propagate in fibers having a fiber diameter which is large compared to the wavelength. If, however, the fiber is sufficiently small, only a single mode will propagate in the fiber, with all other modes being beyond the cutoff wavelength.

*The cross section of a nucleus is a quantity representing the probability of incident neutrons interacting with the nucleus.

fibers, because fused quartz has a higher impurity concentration, resulting in higher spectral losses. For instance, Optosil I has a spectral loss of 12.1 dB/km, and Homosil has a loss of 11.3 dB/km, whereas fused silica materials such as Suprasil I and Suprasil WI (also manufactured by Amersil, Inc.) have spectral losses of 6 and 5 dB/km, respectively.

Several manufacturers of low-loss fibers use a pure silica core with plastic cladding, with the plastic essentially bonded to the core. Various plastics, including polystyrene and acrylic, are also used in making all-plastic fibers. Generally, these fibers are relatively high in loss, although Du Pont has developed plastics which have vastly reduced losses compared to those of the acrylic-polystyrene fibers.

High Loss vs Low Loss

When classifying fibers by losses, two categories are generally used—high and low—although some manufacturers also classify fibers as medium loss. No standard has been developed to define the breakpoints between high and low loss. In this report, fibers with losses of less than 50 dB/km are classified as low loss. Generally, the low-loss fibers are single strand, low numerical aperture, with a small core diameter. Since acceptance angle and core diameter determine the ease of coupling, some of the advantages of the fiber's low loss are offset by coupling losses.

Multimode vs Single Mode

In multimode fibers, the fiber core diameter is orders of magnitude larger than the wavelength of light propagating through it. In single-mode fibers, the core is on the order of 2.5 to 3 μm, or just a few wavelengths, in diameter. The primary advantage of the single-mode fiber is increased bandwidth. In the multimode fiber, many modes will propagate, each having a different velocity of propagation. Thus, a pulse of light transmitted by the fiber will be broadened due to the variation in the modes' propagation times. The pulse-spreading effect reduces the effective bandwidth of the fiber. In contrast, if only a single mode will propagate, the bandwidth will not be limited by the fiber, but by other system components.

Single Fiber vs Bundles

Fibers can be used singly or in bundles. Some bundles use up to several hundred fibers enclosed in a protective jacket. In such a bundle, the individual fibers are generally very small in diameter, thus enhancing flexibility. The use of many fibers increases usable light injection area and allows for improved coupling efficiency. In addition, available bundles have a large NA to further enhance coupling efficiency. Currently available bundles with more than 50 fibers are in the high-loss category, with losses of near 400 dB/km.

Optical Fiber Parameters

This section lists parameters which determine the applicability of optical fiber links in various areas and discusses their importance to optical communications. The current state of the art is given for each parameter and an attempt is made to forecast future improvements obtainable in each area.

Attenuation

Attenuation is the amount of light transmitted by a fiber relative to the amount of light accepted by it. For applications where bandwidth is not a factor, the attenuation determines a maximum length for a communications link for given light transmission and detection systems.

Two principal mechanisms contribute to losses in fibers: absorbtion and scattering. Absorbtion in the near-infrared wavelength region is attributable to the transition-metal ions and to the hydroxyl ion (OH^-). Current manufacturing techniques can keep the glass purity to a few parts per billion (ppb) of the transition metal ions. One ppb of these ions will contribute less than 1 dB/km attenuation to an optical fiber; the hydroxyl ion contributes about 1 dB/km for a concentration of 1 ppm (part per million).[1] The hydroxyl ion, however, causes attenuation in a relatively narrow band centered at approximately 950 nm.

Scattering is caused by inhomogeneous materials, shape imperfections, and bends in the optical waveguide. The losses due to waveguide imperfections and bends can be small. In a study of the overall losses which might ultimately be obtained from optical fibers, Pinnow et al.[2] have shown that losses as low as 1.2 dB/km at 1.06 μm can be obtained for pure fused silica, which is believed to be one of the lowest loss materials for the optical fiber. This figure was obtained as the intrinsic loss of the material in its purest form yet derived. Some

[1] T. Li, "Advances in Optical-Fiber Transmission Research," *Symposium on Optical and Acoustical Micro-Electronics, April 1974* (Polytechnic Press of the Polytechnic Institute of New York, 1975), pp 97-108.

[2] D. A. Pinnow et al., "Fundamental Optical Attenuation Limits in the Liquid and Glassy State With Application to Fiber Optical Waveguide Materials," *Applied Physics Letters*, Vol 22 (May 15, 1973) pp 527-529.

slight improvements may have been achieved since this work was completed in 1973. Ultimately, fibers will probably be made with losses lower than this, but for the immediate future, this appears to be about the best that can be expected.

In stocked commercially available filters, the best attenuation rating obtainable is 6 dB/km as advertised for Corning Glass Works Products 1156 and 1157. Both fibers are of the graded-index type. Corning also advertises that they can supply fibers with losses as low as 2 dB/km. Two other manufacturers have stocked commercially available fibers very close to the 6 dB/km rating, and a total of five U. S. manufacturers have commercially available fibers with less than 20 dB/km attenuation.

Single-mode fibers with attenuation of 250 dB/km are commercially available from Fiber Communications, Inc.

By way of comparison, coaxial cable such as RG-8, which has an outside diameter of 0.490 in. (12.4 mm), has an attenuation of 62 dB/km at 100 mHz and 18 dB/km at 10 mHz. For state-of-the-art coaxial cables, a 5-in. (127.0 mm) diameter cable is required to obtain losses of less than 1.2 dB/km at 100 mHz.

Bandwidth

Bandwidth is a measure of frequency spectrum width which the fiber is capable of transmitting. In many communications links, this is a most important factor, since it determines the link's information transfer rate capability. In this area, the optical fiber has greater potential than conventional coaxial cables, other transmission media, or even waveguides. Reduction of dispersive effects and resultant increase in information bandwidth are high-priority goals in optical fiber research. Toward this end, work is being concentrated on the graded-index and single-mode fibers. (The potential for optical fibers has been stated to be as great as 100 gigabits/sec.[3])

The bandwidth of an optical fiber is related to the pulse-broadening effect. Bandwidth is normally specified at the optical power 3 dB points. Corning relates a 2 nS pulse spreading half maximum to a 200 mHz bandwidth and a 23 mS pulse spreading half maximum to a 20 mHz bandwidth. Pulse spreading is caused by several factors generally called dispersion. Dispersion occurs due to different portions of the transmitted light signal propagating at different velocities. One dispersive effect is due to different path lengths in the fiber. A light ray traveling on the fiber axis will arrive at the fiber receiving end before a ray that is bouncing from one side of the core-cladding interface to the other. Even though a ray may be launched to propagate directly on the axis, some energy disperses into reflective paths due to bends and imperfections in the fiber. Since the reflected rays (Figure 3) travel farther than the direct ray, they arrive at the receiving end of the fiber at different times. Thus, a pulse-spreading effect occurs.

Another cause of pulse spreading is the wavelength dependence of the velocity of propagation of light in the fiber. Thus, if the source used is not of a single wavelength (monochromatic), pulse spreading will occur. Since light-emitting diodes (LED) emit a relatively large spectral width of light, fiber optic links using LEDs will have less information bandwidth than links using single wavelength laser sources. (Use of LEDs and lasers with optical fibers is discussed in the **Interfacing Fiber Optics With Electronics** section.)

A third source of pulse spreading is variations in the velocity of propagation of the different modes of multimode fibers. In the current commercially available multimode fiber, many modes (up to several hundred) will propagate. While the single-mode fiber has a core diameter on the order of a few wavelengths of the light being transmitted, multimode fibers have core diameters several tens of times greater than wavelength. Maurer[4] has defined a relationship which defines the diameter's limit (v) for single-mode step-index fibers:

$$V = \frac{2\sqrt{2\pi r}}{\lambda}\,(\bar{\eta}\,\Delta\eta)^{1/2} \qquad \text{[Eq 2]}$$

where r = core radius

λ = free space wavelength

$\bar{\eta}$ = the average refractive index of core and cladding

$\Delta\eta$ = the difference in refractive indices between core and cladding.

[3] J. McDermott, "Telephone and Data Transmission via Fiber Optics Is Being Pushed," *Electronic Design*, Vol 8 (April 12, 1976), pp 42-47.

[4] R. D. Maurer, "Glass Fibers for Optical Communication," *IEEE Proceedings*, Vol 61, No. 4 (April 1973), pp 452-462.

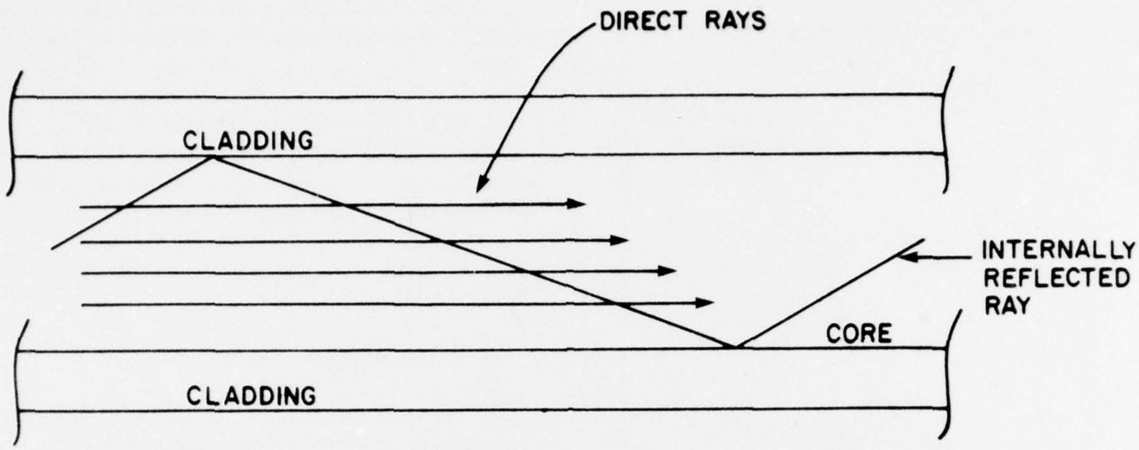

Figure 3. Direct and internally reflected rays.

For values of V below approximately 2.4, the fibers propagate only a single mode.

If a single-mode fiber is driven by a monochromatic light source, the only major source of pulse spreading is multipath and waveguide imperfections. Manufacturing processes are such that these spreading effects can be kept small. It has been predicted that fibers can be manufactured which will be capable of information bandwidths as high as 10^{11} bits/sec/km (requiring a bandwidth of 50,000 mHz/km).[5] Of those available commercially, the bandwidth obtainable varies from 20 mHz/km for Corning 1025 and 1028 fibers to 400 mHz/km for Corning 1153 and 1159 fibers.

Another type of wideband fiber in addition to the single-mode fiber is the graded-index fiber. In these fibers, the variation in index of refraction versus radius introduces a compensation factor, compensating (to a degree) for variations in mode velocity (or in multipath lengths). It has been determined that the index of refraction gradient relative to fiber radius is critical to optimizing bandwidth when a narrowband source is used.[6] The optimum index profile has been determined to be approximately parabolic. Figure 4 shows bandwidths which can be expected versus the index gradient parameter α. The quantity α for graded-index fibers is defined in the expression

$$\eta^2(r) = \eta^2(0)\,[1 - 2\Delta(\frac{r}{a})^{\alpha}] \qquad \text{[Eq 3]}$$

where η = index of refraction

$\eta(0)$= index of refraction at the center of the fiber

r = radial distance

Δ = constant.

Thus, if α equals 2, a parabolic form is realized. Figure 4 shows that an α value of approximately 2.2 is optimum for maximum bandwidth and that more than 10 gigabits/sec is possible for monochromatic sources and a perfectly straight fiber in 1-km lengths.

In currently available fibers, the state of the art in regard to bandwidth is set by the Fiber Communications, Inc. single-mode fiber. This company claims a bandwidth capability of several gigahertz-kilometers. This fiber, however, has an NA of 0.10 to 0.12, which results in a maximum acceptance angle of 14 degrees; this angle, when coupled with the extremely small diameter (2.5 μm) of the core, results in very low coupling efficiency when used with LEDs. A laser source is therefore essential to improve coupling efficiency to enable usable light transmission levels. However, use of a laser creates other problems which are discussed in the **Interfacing Fiber Optics With Electronics** section.

In graded-index fibers, the best commercially available fibers have a capability of 400 mHz-km, as claimed for Corning 1151, 1157, 1153, and 1159 fibers. In step-index fibers, the Galileo Galite 5000 fiber is claimed to have greater than 100 mHz-km bandwidth

[5] W. B. Bielawski, "Low-Loss Optical Waveguides, Current Status," *Electro-Optical Systems Design*, Vol 5 (April 1973), pp 22-28.

[6] R. B. Keck, *Transmission Properties of Optical Fiber Waveguides*, Report L-1668 (Corning Glass Works, 1975).

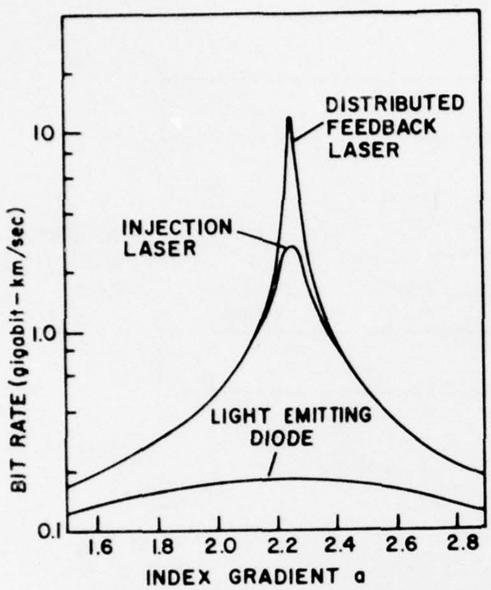

Figure 4. Information-carrying capacity as a function of the gradient parameter α for graded-index fiber.

capability, which is the highest for commercially available fibers.

Advantages and Disadvantages of Fiber Optic Communications

An optical transmission system using the optical fiber as a transmission medium has advantages over conventional wire and cable in many areas. These include:

1. The optical fiber does not generate electromagnetic interference/radio frequency interference (EMI/RFI), nor is it susceptible to outside EMI/RFI. Consequently, the optical fiber is often used to transmit data in intense electromagnetic environments.

2. Since the fiber does not conduct, complete electrical isolation is achieved, thereby eliminating ground loop problems.

3. The optical fiber is much safer to use around explosives or highly flammable materials.

4. The optical fiber is much more difficult to tap than a wire or cable, thus affording a greater degree of security.

5. The fiber is lighter and smaller than wire and cable, and is potentially less expensive than coaxial cable.

6. Since the frequency of light is several orders of magnitude higher than any carrier which can be used on wire, cable, or conventional waveguides, the bandwidth potential for optical fibers is greater.

7. Crosstalk is completely eliminated in optical fibers.

Some disadvantages of optical fibers are:

1. For most applications, the overall optical link is currently more expensive than its conventional equivalent.

2. Far fewer standard optical link components are available off the shelf.

3. The optical link adds complexity in coupling in and out of the fiber.

4. In some instances, fiber flexibility is less than that of cabling.

Interfacing Fiber Optics With Electronics

Optical Transmitters

Unlike conventional communications links which use wire and cable, the fiber optic link does not directly use the energy transmitted, but converts electrical signals to light signals and vice versa. In choosing an optical transmitter, one must consider its compatability with the fiber based on factors such as fiber geometry, loss spectrum, bandwidth requirement, source-fiber coupling, etc. The light source for the optical transmitter can be one of the following:

1. Laser, solid state

2. Laser, gas

3. Laser, semiconductor

4. LED

5. Incandescent source.

The solid-state laser most suitable for fiber optic links is the Nd:YAG laser. This coherent optical source, which can be used with either single-mode or multimode fibers, has several advantages:

1. It operates at a wavelength of 1.06 μm, which is the wavelength at which a silica fiber has its lowest loss.

2. It has a narrow emission spectral width; thus, less material dispersion occurs in the fiber and data can be transmitted at a higher rate.

3. A collimated laser beam has a divergence of less than 1 milliradian and can therefore be coupled into the fiber with close to 100 percent efficiency.

4. Obtaining a single-frequency, single-mode output from an Nd: YAG laser is easy.

Although high-power laser sources are usually bulky and inefficient, an Nd:YAG laser can be miniaturized using a technique known as end-pumping with an LED.[7] The disadvantage of a miniaturized laser is that output laser power of 10 W or more is reduced to 2 to 5 mW.[8]

A very undesirable feature of the solid-state laser is that it must be used with an external modulator. In choosing an external modulator, one must consider the speed of modulation. The acousto-optic bulk-type modulator is best suited for modulation speeds below 100 megabits/sec.[9] In an acousto-optic modulator, light is diffracted or reflected by a phase grating created by a photoelastic effect on an acoustic wave propagating through certain material. Efficient high-speed modulation is achieved by an electro-optic modulator having a bandwidth of a few gigahertz.[10] In an electro-optic modulator, an applied electric field induces a change in the refractive index of an electro-optic material which, in turn, causes a phase modulation of the optical beam. Additional factors such as the modulator's compatibility with the rest of the system, the ease of coupling to the source and fiber, and the additional cost must be considered.

Semiconductor lasers are also well suited for fiber optic transmission systems. Among their many attributes are small size, ruggedness, efficiency, and simplicity in modulation by directly varying the injected current. The semiconductor laser diode, however, must be judiciously used due to its relatively short lifetime (1000 hours typical to 3000 hours maximum). At present, the most promising laser diode for continuous operation is the double-heterostructure (DH) design consisting of five layers of $Al_xGa_{1-x}AS$ semiconductor material. ($Al_xGa_{1-x}As$ represents aluminum-gallium-arsenic where x is the mole fraction of aluminum and the subscripts define percentages of material used.)[11]

A DH laser diode has some very interesting features. By changing the mole fraction of aluminum, it is possible to control the wavelength of emission from the ultraviolet to near infrared.[12] Therefore, the laser diode is usually made to emit at 0.8 to 0.9 μm, which is a region of low fiber loss. The spectral width of the emission is typically less than 20 Å and is sufficiently narrow that material dispersion is unimportant for long-distance fiber transmission. The emission also has a narrow beam width (typically 20 degrees) so that more than 50 percent coupling efficiency can be obtained.

Another interesting feature is that the DH laser diode is the most efficient of the optical sources listed above. For example, the DH laser diode can convert 0.2 to 0.5 W of input power to 10 to 50 mW of optical power, while the Nd:YAG laser requires an input of 1 to 2 W for 2 to 5 mW of output, and the LED requires 0.2 to 0.5 W of input for 5 mW of output.[13]

However, the semiconductor laser diode is not a reliable device. Its failure can come suddenly or gradually, regardless of environment or mode of operation (continuous or pulsed). Sudden degradation has been found to be a result of high current density (approximately 700 A/cm^2 for pulsed operation at room temperature)

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[7] C. A. Burrus and J. Stone, "Single-Crystal Fiber-Optical Devices: a Nd:YAG Fiber Laser," *Journal of the Optical Society of America*, Vol 65 (October 1975), p 1221; and C. W. Reno, "Laser Diode Pumped Nd^{3+}: YAG Laser," *Journal of Quantitative Electronics*, Vol QE-11, No. 9 (September 1975), p 160.

[8] S. E. Miller, E. A. J. Marcatili, and T. Li, "Research Toward Optical-Fiber Transmission System," *IEEE Proceedings*, Vol 61 (December 1973), pp 1703-1751.

[9] Scibor-Rylski, "Calling Out Light Modulators," *Optical Spectra*, Vol 10 (February 1976), pp 30-33.

[10] A. Waksberg, "Optimization of a Laser Communications System Using Electrooptic Modulation," *Journal of Quantitative Electronics*, Vol QE-11, No. 9 (September 1975), pp 778-782.

[11] Miller, Marcatili, and Li; and M. Nakamura et al., "GaAs/GaAlAs Double-Heterostructure Injection Lasers With Distributed Feedback," *Journal of Quantitative Electronics*, Vol QE-11, No. 7 (July 1975), pp 436-439.

[12] J. T. Boyd and D. B. Anderson, "Distributed-Feedback Coupling in $Ga_{1-x}Al_xAs$ Doubleheterostructure Lasers: Effect of Aluminum Concentration," *Applied Optics*, Vol 14 (September 1975), pp 2199-2202.

[13] S. E. Miller, E. A. J. Marcatili, and T. Li, "Research Toward Optical-Fiber Transmission System," *IEEE Proceedings*, Vol 61 (December 1973), pp 1703-1751.

at the junction of the diode. Although gradual degradation is not very well understood, a great deal of progress is being made.[14] One current area of high priority research is development of techniques for increasing the lifetime of the laser diode. Success in this area has been achieved in the laboratory by Bell Telephone Laboratories. Although the work is currently undocumented, future successful commercial applications appear to be imminent. In addition, RCA Research Laboratory is currently involved in research to develop an injection laser diode with a 10,000-hr lifetime.

Currently, the LED is the light source in most fiber optic links, and the industry is placing high priority on improving LEDs by increasing usable light output and bandwidth capability, and reducing cost. LEDs with high output optical power are commercially available at relatively low prices. Unless laser diodes with long lifetimes are made commercially available, LEDs may be considered the most suitable optical source for commercial fiber optic communications.

The primary parameters of interest in regard to establishing the state of the art of LEDs are the light power emitted within a specified cone and the frequency-response-related parameters (risetime and falltime). From the standpoint of usable emitted power, two basic types of LEDs are available: the flat-geometry LED with dome, and the edge emitter.[15] Figure 5 shows a greatly magnified sketch of the flat-geometry LED, which emits light through a one-half spherical pattern (2π steradians) since the anode material absorbs light in that direction. Figures 6 and 7 show the same diode with the addition of domes and a parabolic reflector to concentrate the emitted light to a small-angle radiation pattern. These diodes currently will yield comparable performance. Of currently available LEDs, about 1/3 mW into a 10 degree cone is the best obtainable. In addition, LEDs have wide emission spectral width (350 Å). Therefore, in order to increase the light power transmitted through an optical fiber, many modes must be allowed to propagate. Consequently, LEDs must be used with multimode fibers having large numerical apertures.

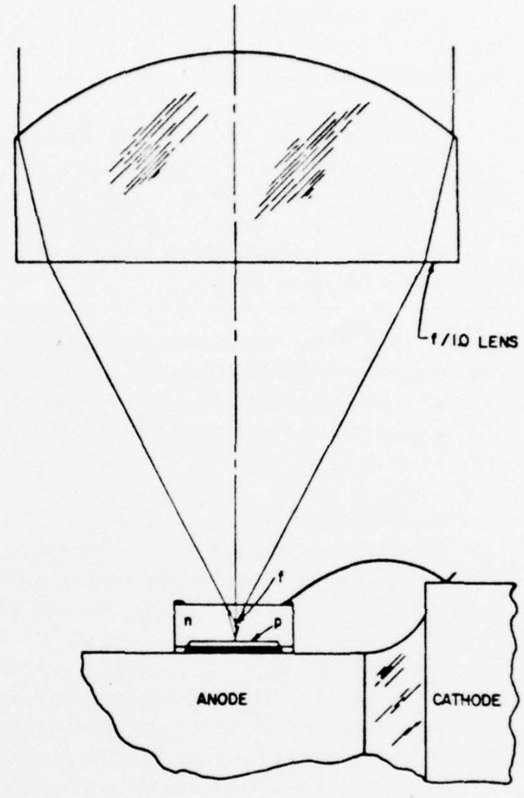

Figure 5. Flat-geometry LED.

Unfortunately, low-loss fibers have small numerical apertures (0.14 to 0.3), thus making efficient coupling a very difficult problem. An edge-emitting diode (Figure 8) can be used to overcome this problem. The elliptical reflector of an edge emitter enables more output power to be concentrated in a significantly narrow cone, thus making more effective coupling into a low-loss fiber possible. Biard[16] has predicted that an idealized edge emitter will project 70 percent of its total output power into a 5.8 degree half-angle cone. The edge emitter also has a lower fabrication complexity and better mechanical tolerance control than the dome-type LED. However, the quantum efficiency and total output power of an edge emitter are not as high as those of the dome type.

[14] J. Butler and C. S. Wang, "Threshold Behavior of CW GaAS-AlGaAs Injection Lasers," *Journal of Quantitative Electronics*, Vol QE-12, No. 3 (March 1976), pp 165-168.

[15] H. Kressel and M. Ettenberg, "A New Edge-Emitting (AlGa) as Heterajunction," *IEEE Proceedings*, Vol 63 (September 1975), pp 1360-1361; and J. R. Biard, *Optoelectronic Aspects of Avionic Systems*, Final Technical Report AFAL-TR-73-164 (Air Force Avionics Laboratory, April 1973).

[16] J. R. Biard, *Optoelectronic Aspects of Avionic Systems*, Final Technical Report AFAL-TR-73-164 (Air Force Avionics Laboratory, April 1973).

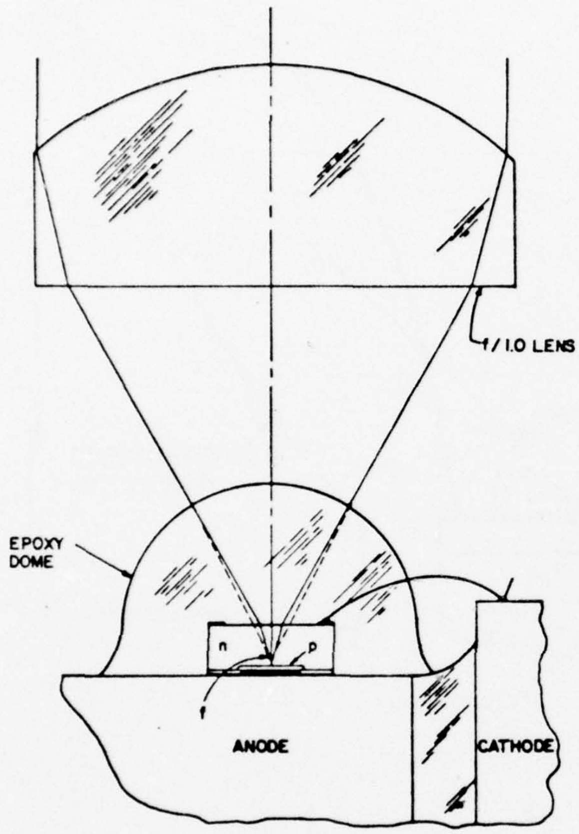

Figure 6. Flat-geometry LED with epoxy dome.

The fastest risetime of a commercially available LED, Monsanto ME-3, is on the order of 1 nsec, which is faster than most of the commercially integrated circuits. Because of this fast response time, direct modulation achieves a bandwidth of several hundred megahertz.[17]

The best obtainable risetimes and falltimes of currently available LEDs are on the order of 10 nsec, which would yield an inherent upper frequency limit of approximately 35 mHz. Speed-up circuits, however, can be employed to increase the transmitted bandwidth to 100 mHz.

Incandescent sources have seen very limited application and are therefore not discussed.

Detectors

A detector is necessary at the receiving end of the optical fiber to convert the received light into voltage or current signals. This can be accomplished by a photodiode, phototransistor, phototube, or photomultiplier. The phototube is not sensitive enough for most applications. A photomultiplier is excessively large and expensive and requires a high voltage power supply. In addition, the frequency response of the photomultiplier is insufficient for high data rate communications applications. Thus, the photodiode and phototransistor are the only choices for high data rates. It has been shown that a properly designed silicon planar photodiode is optimum for use in optical data transmission.[18] Risetimes as low as 1 nsec have been obtained, yielding transmission capability to 350 megabits/sec. In addition, the photodiode provides adequate sensitivity for most applications.

Integrated Optical Circuits

The promise of extensive usage of fiber optics technology in communications has stimulated research in the area of integrated optics. Integrated optics involves using extremely small optical waveguides to interconnect various miniature solid-state optical components on a single substrate. Components include sources, detectors, modulators, and associated integrated electronics to complete a communications link. Sources include LEDs, semiconductor lasers, or thin-film lasers. Integrated optics offers advantages of decreased size and weight, potential improvements in reliability, and reduced susceptibility to environments including EMI, mechanical vibration, and temperature extremes.

The technology includes coupling optical fibers with other components. One promising aspect is the possibility of efficient coupling to the extremely small single-mode and low-loss fibers. Various passive elements such as lenses, gratings, and frequency mixers can be integrated with the couplers.

[17]C. A. Burrus, T. P. Lee, and W. S. Holden, "Direct-Modulation Efficiency of LED's for Optical Fiber Transmission Application," *IEEE Proceedings*, Vol 63 (February 1975), pp 329-331; and Y. S. Liu and D. A. Smith, "The Frequency Response of an Amplitude-Modulated GaAs Luminescence Diode," *IEEE Proceedings*, Vol 63 (March 1975), pp 542-544.

[18]J. R. Biard, *Optoelectronic Aspects of Avionic Systems*, Final Technical Report AFAL-TR-73-164 (Air Force Avionics Laboratory, April 1973).

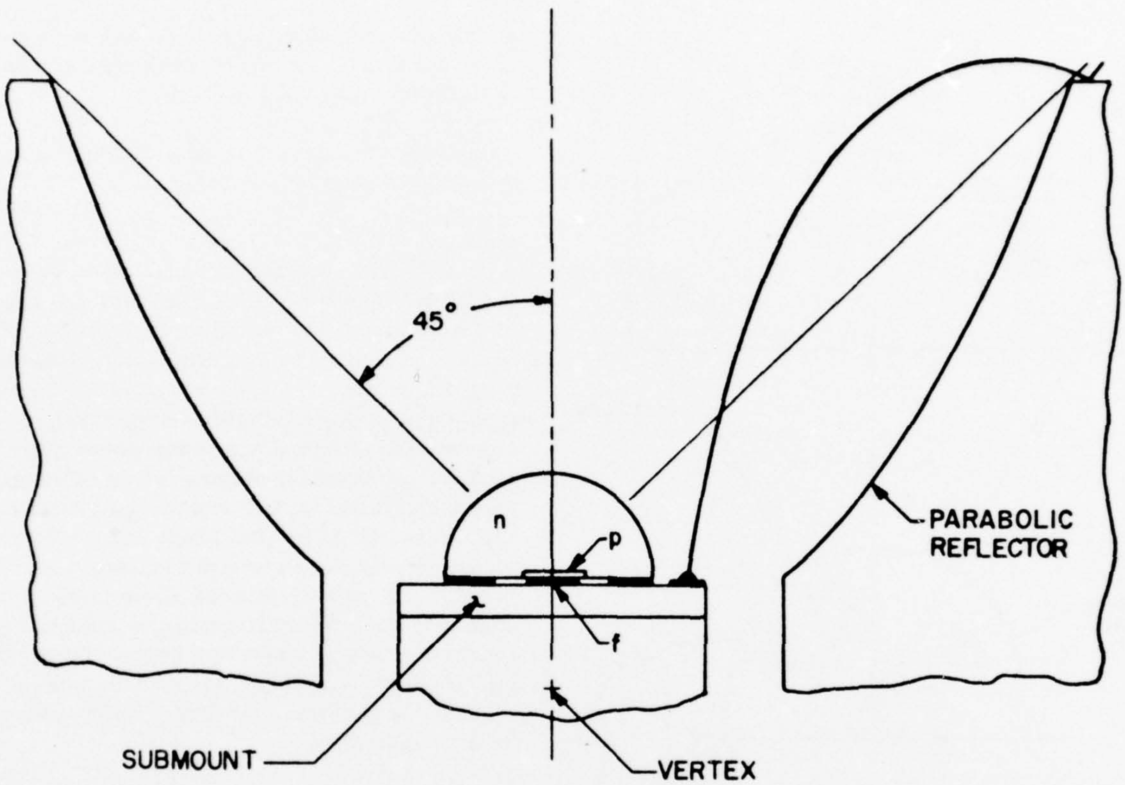

Figure 7. Dome LED with reflector.

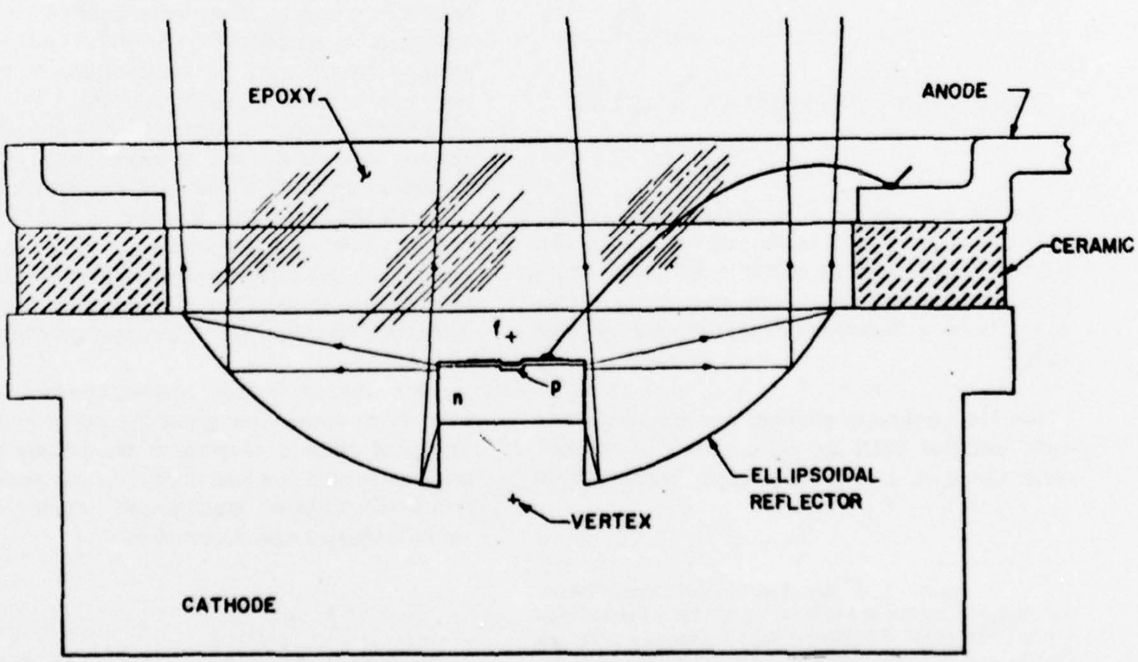

Figure 8. Edge-emitting LED with reflector.

Susceptibility of Optical Fibers to Nuclear Radiation

Recently, several potential advantages of using optical fibers in military communications sytems have prompted considerable interest in their use. Of particular interest has been the use of optical fibers to eliminate EMI/RFI, since the effect of such an electromagnetic pulse on the fiber itself would be expected to be very small.

Since some military communications systems must have the potential to operate in a nuclear radiation environment as well as environments subjected to EM/RF pulses, the effects of nuclear radiation must be considered when evaluating the feasibility of optical fiber communication systems in such situations. This section reviews the state of the art concerning the effects of nuclear radiation on optical fibers.

Nuclear radiation can be classified into four general types depending on the interactions with matter:*

1. Heavy charged particles (e.g., protons and alpha particles)

2. Light charged particles (e.g., energetic electrons)

3. Gamma rays and X-rays

4. Neutrons.

Since the range of heavy charged particles is usually rather small, they do not pose a serious threat as external sources. For this reason, most of the work** on the effect of nuclear radiation in optical fibers and fiber materials is concerned with the last three types of radiation.

It has been known for some time that radiation can produce severe changes in optical materials, and extensive work on the effects of nuclear radiation on optical materials has been done. The principal concern at present is the manner in which and the degree to which the effects of nuclear radiation may interefere with or degrade communication via an optical fiber. For this reason, particular emphasis is given to tests of available optical fibers and fiber material.

Irradiation of optical fibers with X-rays, gamma rays, energetic electrons, or neutrons can result in two principal types of interference with optical signals being transmitted through the fiber: (1) luminescence (light generation within the fiber material itself), resulting in a spurious light signal which may in some cases be as large as or larger than the transmitted signal; or (2) darkening of the optical fiber, resulting in an increase in the attenuation coefficient of the fiber with subsequent decreased transmission of optical signals (in some severe cases, to the extent that the optical fiber may become essentially opaque).

The fact that optical materials exhibit luminescence when excited by ionizing radiation is the basic principle of scintillation detectors used to detect ionizing radiation. Although the materials in optical fibers are not particularly good scintillators, they do in fact exhibit luminescence when exposed to nuclear radiation. Luminescence is thought to result from recombination and de-excitation processes following ionization, or from Cerenkov radiation.[19]

Studies with X-rays indicate that the time constants for the decay of luminescence following a rapid X-ray pulse appear to depend only on the type of fiber and not on the intensity of the luminescence.[20] The intensity of luminescence was found to be greater during electron irradiation than during X-ray excitation at the same dose rate (the ratio varying with the type of fiber).

The luminescence is distributed over a spectrum of wavelengths commonly used in optical fiber communication systems and exhibits a characteristic decrease in intensity from shorter to longer wavelengths. The fact that the luminescence is distributed may make it difficult to filter out.

Radiation-induced darkening of optical fibers is due to the formation of color centers which cause a reduction in light transmission over a spectrum of wavelengths. These color centers tend to fade with time

*Some aspects of the interaction of these radiations with matter are discussed in Appendix B.

**The following references from the list of cited references at the end of the report deal specifically with the effect of nuclear radiation on optical fibers: Blake et al.; Cohen and Lanzerotti; Evans and Sigel (2); Friebele, Ginther, and Sigel; Lukesh; Mattern; Mattern et al. (3); Maurer et al.; Presby; Shah; Sigel; Sigel and Evans; Sigel et al.; Treadway, Passenheim, and Kitteran; Wall; Wall and Bryant; and Watkins.

19. P. L. Mattern et al., "The Effects of Radiation on the Absorption and Luminescence of Fiber Optic Waveguides and Materials," *IEEE Transactions on Nuclear Science*, Vol NS-21 (December 1974), pp 81-112.

20. J. A. Wall and J. F. Bryant, *Radiation Effects on Fiber Optics*, AFCRL-TR-75-0190, ADA013786I9GA (Air Force Cambridge Research Laboratories, April 1975).

after exposure to radiation. The rate of the fading depends on the particular fiber material and the wavelength of interest.

The increased absorption due to irradiation by X-rays, gamma rays, and electrons is apparently greatest shortly after the pulse and tends to decrease to some relatively permanent value after a period of time. For this reason, the absorption is often discussed in terms of transient absorption and permanent absorption (usually the increased absorption which remains after a length of time, e.g., 24 hrs), although the fading of the color centers may continue indefinitely. The transient absorption may be several orders of magnitude greater than the permanent absorption. The increased attenuation varies with wavelength (as does the intrinsic attenuation of unirradiated fibers). This may be an important consideration in the selection of an emitter for a communication system.

Most of the existing data concerning the luminescence and absorption induced in optical fibers by nuclear radiation have been obtained using ionizing radiation. Additional data on the absorption induced have been taken using fast neutrons; however, there do not appear to be any data for thermal neutron irradiation. Furthermore, there do not appear to be any data concerning luminescence and transient absorption during neutron irradiation.

The fact that permanent absorption losses induced by energetic electrons, gamma rays, and fast neutrons appear comparable when compared on the basis of induced ionization[21] does not mean that all three have the same ability to do damage. Since the interactions that the various radiations have with matter often depend on the energy of the incident radiation, the effects for a particular type of radiation would be expected to depend on the energy of the incident radiation. Since experimental results are quite often obtained for a certain energy, it would seem that extrapolation to vastly different energies should be done with caution.

Furthermore, the change in transmission with dose is not a linear function (although at low doses it may be very nearly so); hence, extrapolation to doses which differ greatly from those for which data have been taken should also be done with caution. For moderate dose rates, the luminescence appears to be proportional to the instantaneous dose rate, and the permanent absorption appears to be independent of the dose rate; this may not be true, however, at much higher dose rates.

The effect of nuclear-radiation-induced losses in optical fibers depends strongly on fiber construction. For purposes of this discussion, classifying optical fibers into four general types based on fiber composition is convenient:

1. Low-loss fused silica fibers. These fibers are drawn from fused silica. Included under this category of optical fiber materials are high-purity synthetic silica and lightly doped silicas. The attenuation in unirradiated fibers is typically less than 100 dB/km.

2. Commercial-grade glass fibers. These fibers are drawn from "standard" optical glasses such as borosilicates and lead silicates. These quite often consist of a core of heavy metal silicate such as lead or barium with a borosilicate cladding. The intrinsic attenuation in unirradiated fibers is on the order of 1000 dB/km.

3. Cerium-doped glass fibers. These fibers are drawn from glass which has had a small amount of cerium (often in the form of cerium oxide) added to the glass melt before drawing. The cerium increases the fiber's resistance to radiation-induced transmission losses. (These fibers are in the experimental stage and do not appear to be commercially available.)

4. Plastic fibers. These fibers have cores of either polymethylmethacrylate (PMMA) or polystyrene and a cladding of lower refractive index polymer. They are lightweight and inexpensive but have very high intrinsic attenuation at wavelengths greater than 800 nm. Their attenuation in the visible range is about 1200 dB/km.

The radiation effects observed appear to be different for each type of fiber.

Pure fused silica appears to be quite resistant to radiation-induced attenuation. On the other hand, borosilicate glasses are quite susceptible to neutron damage, probably due to the high neutron cross section of boron. The addition of small amounts of cerium makes most glasses more resistant to permanent radiation damage; however, addition of larger quantities of cerium may result in greater intrinsic attenuation in the unirradiated optical fiber.[22]

[21] P. L. Mattern et al., "Absorption Induced in Optical Waveguides by Pulsed Electrons as a Function of Temperature, Low Dose Rate Gamma and Beta Rays, and 14 MeV Neutrons," *IEEE Transactions on Nuclear Science*, Vol NS-22, No. 6 (December 1975), pp 2468-2474.

[22] B. D. Evans and G. H. Sigel, Jr., "Radiation Resistant Fiber Optic Materials and Waveguides," *IEEE Transactions on Nuclear Science*, Vol NS-22, No. 6 (December 1975), pp 2462-2467.

At present, the optical fiber materials which appear to be most resistant to permanent radiation damage are those in categories 1, 3, and 4 above. Commercial glass fibers seem to be very radiation-sensitive and would appear essentially unusable in high radiation environments; however, they may be suitable for applications at low levels of radiation.

Whether the permanent absorption in an optical fiber will interfere with its function depends on the induced attenuation which can be tolerated. Thus, the dose to which the fiber is to be subjected, the induced attenuation per unit length per unit dose, and the length of the fiber must be considered. For low dose environments and short lengths, the choice of fibers and fiber materials will be greater than for those applications which require either low induced attenuation or longer fiber lengths. In the latter cases, the selection of fibers and fiber materials is much more limited.

In some cases, knowing the induced luminescence in a particular fiber at wavelengths of interest in fiber optics systems is also important. Even the best optical materials (e.g., high-purity fused silica) exhibit high levels of luminescence. Cerium has even been used in scintillators to enhance the efficiency of those materials. Since the possible effect of cerium doping on luminescence in optical fibers does not appear to have been evaluated, further investigation may be necessary in applications where luminescence may be a problem.[23]

The suitability of a particular optical fiber also depends on the response characteristics required of the communication system. In applications where operation during or shortly after a nuclear radiation pulse is not a requirement, the permanent absorption induced by the nuclear radiation would be the principal concern. In applications where operation during or shortly after a nuclear radiation pulse is a requirement, greater attention would be given to the magnitude of the luminescence and transient absorption, as well as the fiber's recovery time.

Although the data are by no means complete and several aspects of nuclear radiation effects need further consideration, a considerable amount of data is available for designing with optical fibers. A number of optical fibers have been tested under a variety of nuclear radiation conditions. Irradiation with X-rays, gamma rays, and energetic electrons of various energies for various dose rates and total doses has been performed. The data on the effects of neutron irradiation are much more limited in availability, and data on the effects of thermal neutrons (which could arise in underground systems) appear to be totally lacking. In general, the extant data do provide the designer with a basis for evaluating the suitability of optical fibers for a variety of conditions. Chapter 3 describes ongoing DOD research in the nuclear radiation area, as well as other areas of fiber optics research.

[23] R. L. Cohen and L. J. Lanzerotti, "Noise in Fiber Optics Communications Systems Induced by Ionizing Radiation," *Applied Optics*, Vol 13, No. 10 (October 1974), pp 2190-2191.

3 SUMMARY OF R&D IN FIBER OPTICS

DOD-Supported R&D in Fiber Optics

A study was performed to determine the extent of work being performed by various DOD agencies in the area of fiber optics for communications. The study was performed partially by telephone contacts, but largely by an automated work unit summary prepared by DDC. Only work units which might result in advancement of the state of the art were considered. Thus, some work units which were concerned primarily with development of related components such as couplers, LEDs, photodiodes, etc., are included. The study revealed that DOD has funded (for the current year, FY77) 89 work units with a total outlaw of $10.6 million, including both in-house and contracted work.

The U. S. Naval Electronics Laboratory Center (NELC), which DOD has designated the lead laboratory in this technological area, is responsible for 15 work units and more than one-half of the total funding. The U. S. Army Electronics Command (ECOM) has the second highest number of work units—13; Harry Diamond Laboratories (HDL) is third with 6; and the Naval Research Laboratory (NRL) is fourth with 5. The following sections summarize the technological areas being investigated by these and other groups. Appendix C contains a list of other government agencies and organizations performing or responsible for DOD-sponsored research.

NELC

NELC is performing studies in the following areas:

1. Use of fiber optics for Defense Communications Systems (DCS) applications, including a feasibility study and adaptation of existing hardware for DCS use

2. Development of a fiber optic communications link for multi-channel, high-speed, digital data transmission

3. Development of 5-km-long fiber optic cables for use with sonobuoys

4. Use of fiber optics on a glide bomb

5. Development of a complete line of fiber optic components qualified for military use, including cables, connectors, transmitters, receiver modules, light sources, and test and evaluation techniques

6. Development of technology and system demonstration for air-borne fiber optic internal aircraft signal transmission

7. Development of manufacturing process for fiber optic cable suitable for military aircraft avionics systems.

8. Development of technology and materials for integrated optical circuits on miniature substrates to interconnect optical components and interlink communications systems

9. Development of a computer to peripheral fiber optic digital and video data communications link

10. Development of undersea fiber optic cable for use as tow cable, bottom-laid cable, and suspended cable in surveillance systems

11. Development of undersea cable for torpedo guidance.

ECOM

ECOM's fiber optics research includes the following:

1. Development of solid-state laser devices for coupling to low-loss fiber optics

2. Development of a fiber optic replacement link for a 26-pair cable

3. Development of long-haul fiber optics for pulse code modulation (PCM) cable communications system

4. Study of the feasibility of using fiber optic cables in secure tactical cable links without the use of encryption equipment

5. Development of standardized fiber optic transmission lines and fitting

6. Development of new special-purpose lasers which can have fiber optic light source applications

7. Investigation of radiation-induced transparency changes in optical fibers for use as radiation dosimeters

8. Study of Faraday effect optical modulators for fiber optic applications.

HDL

HDL is performing work in the following areas:

1. Development of a 200-mHz bandwidth fiber optic telemetry link which is radiation tolerant

2. Identification of nuclear radiation effects on the performance of fiber optics in specific applications

3. Development of fiber optic data links for specific applications.

NRL

NRL is performing research in the following areas:

1. Coordinated research program to develop infrared integrated optics

2. Development of radiation-resistant optical glasses for use in optical fibers in military systems

3. Development of techniques leading to improved optical fibers

4. Development of single-mode fiber to thin film waveguide coupler

5. Development of multi-terminal fiber optic data communications systems which use a single laser source.

Other

DOD-sponsored research being performed by other organizations includes the following:

1. Development of a wideband (greater than 100 mHz) fiber optic data transfer link

2. Theoretical and experimental investigation of mechanisms influencing propagation of light in materials

3. Investigation of purely optical transmission of signals without conversion of optical signals into electrical signals

4. Development of solid-state lasers specifically for use with fiber optics

5. Study of radiation damage mechanisms and development of radiation-hardening techniques for optically coupled isolators, LEDs, and photodetectors

6. Development of engineering data on fiber optic waveguides and associated components in a radiation (gamma, gamma dose rate, and neutron) environment

7. Development of improved techniques for coupling light into low-loss optical fibers

8. Development of lightweight and low-cost optical fibers for field Army environments

9. Development of a fiber optic ground station to missile communications and control link capable of being payed out by the missile

10. Investigation of applicability of fiber optics for Naval air programs

11. Research toward development of new fabrication processes for low-loss self-focusing fiber optic waveguides

12. Theoretical analysis of optical waveguides

13. Study of signal to noise ratios for fiber optic systems in EMP environments

14. Investigation of space flight applications of fiber optics

15. Studies in maximizing information-handling rates for fiber optic channels

16. Study of the use of fiber optics for electromagnetic compatibility improvements on submarines

17. Confirmation of the luminescence levels generated in irradiated fibers of longer lengths.

Non-DOD-Sponsored R&D

The Department of Commerce Office of Telecommunications Policy (OTP) has recently initiated a comprehensive study to determine the impact of optical fiber technology on the delivery of telephone, television, and information services. Current technical and economic data will be used to evaluate system design optics feasible during the next 20 years.

Cable television firms have started to use optical fiber communications links. Teleprompter Manhattan Cable Co.'s use of an 800-ft (243.8 m) length of fiber optic cable to link the top of a tall apartment building in Manhattan to Teleprompter's central processing offices 34 floors below is reportedly a first in the U. S. television industry. The quality of transmission is reported to be excellent. The light source used is an LED which is modulated by video signals.

A British cable television company has also begun using a fiber optic cable in "live" distribution. Rediffusion, the company which installed the cable, reports that this is the first such usage in Great Britain. Cable length is 1.427 km; two fibers are used in the cable, each carrying a full-bandwidth color television signal. LEDs are used as light sources along with Corning Glass Works step-index fibers. The two fibers have losses of 18 and 22 dB respectively for the 1.427-km link at the 900-nm wavelength used.

4 CONCLUSIONS

Fiber optics are potentially capable of fulfilling many communications applications, including Corps of Engineers applications in monitor and control systems of facilities or buildings.

Fiber optics offer numerous advantages over conventional wire or cable links, including freedom from EMI, electrical isolation security, and safety enhancement in explosive or flammable material areas. The bandwidth capability of fiber optics systems can be in the multigigahertz range, and transmission losses can be lower than for conventional wire or cable systems. These and other advantages will result in continuing R&D and eventual assumption of a large part of the general communications burden by fiber optics.

A large amount of work has been done in evaluating optical fibers in nuclear radiation environments, but the effects of thermal neutrons have not been isolated.

The current level of R&D in advancing the state of the art in fiber optics technology is extensive in both industry and government.

APPENDIX A: SUMMARY OF COMMERCIALLY AVAILABLE OPTICAL FIBERS

Manufacturers listed in various buyers' guides and directories were asked to provide information on their available mass-produced optical fibers. The completeness and accuracy of the information presented herein thus depend on product information supplied directly by the manufacturers. In addition to the companies listed, numerous other companies manufacture fibers for purposes other than communications or for special-order only.

Where possible, pricing information is included. It should be noted, however, that the prices of optical fibers will change as larger quantity production and improved techniques are realized.

1. American Optical Corp.
   Fiber Optics Division
   Southbridge, MA 01550

Product line includes a glass fiber optic cable for use in data transmission systems and fiber scopes, clad rod, image conduit, and other related components.

The multimode optic cable has the following characteristics:

Attenuation—less than 400 dB/km at 900 mm

Number of fibers—200 (approx.)

Fiber size—75 μm (0.003 in.)*

Index profile—step

Numerical aperture—0.66

Cable outer diameter—0.095 in. (2.41 mm)

Pricing for an unterminated cable is as follows:

Less than 500 ft (152 m) = \$2/ft (\$6.56/m) + \$50 setup

500 to 2500 ft (152 to 762 m) = \$1.50/ft (\$4.92/m) + \$50 setup

2. E. J. Du Pont de Nemours & Co., Inc.
   Plastic Dept.
   Wilmington, DE 19898

Product line includes a cable containing seven plastic fibers (PFX 01715) and a silica core/plastic clad fiber (PFX S108R). Table A1 summarizes the characteristics of the two multimode fibers.

3. Corning Glass Works
   Telecommunications Product Department
   Corning, NY 14830

Product line includes high-loss flexible multifiber cables; low-loss, 19-fiber, step-index bundles; low-loss, seven-fiber, step-index cables; and low-loss, seven-fiber, graded-index cables.

Standard cables can be supplied with attenuation as low as 6 dB/km. For special applications, fibers with attenuations as low as 2 dB/km (at 1060 mm) and bandwidths as high as 1 GHz/km can be supplied. Table A2 summarizes the characteristics of the fibers and multifiber bundles.

Table A1
Characteristics of DuPont Fibers

	PFX 0715	PFX S108R
Attenuation (dB/km)	470 @ 656 nm	100 @ 700 nm
Number of Fibers	7	1
Fiber Size, in. (mm)	0.0146 (0.3708)	0.024 (0.610)
Cable Size (Outer Diameter), in. (mm)	0.075 (1.91)	0.075 (1.91)
Numerical Aperture	0.53	0.4
Terminations	—	—
Price/Meter	\$3.30 \$495 min order	
Index Profile	Step	Step
Fiber Materials	Plastic	Silica core/ plastic cladding

*Fiber and cable sizes are given in both SI and non-SI units for the convenience of the user. The unit given first is the unit provided by the manufacturer, while the unit in parentheses is the conversion. Other measurements are given in SI units only, as provided by the manufacturers.

Table A2
Characteristics of Corning Fibers and Multifiber Bundles

Product Number	Attenuation, dB/km	Number of Fibers	Fiber Size, mm (in.)	Index Profile	Numerical Aperture	Cable Outer Diameter, mm (in.)	Bandwidth MHz/km	Price/ Meter
Fibers								
1300	20	7	0.125 (0.005)	Step	0.18	5 (0.2)	20	$10.00
1302	20	7	0.125 (0.005)	Graded	0.16	5 (0.2)	200	13.50
1010	20	6	0.132 (0.005)	Step	0.16	5 (0.2)	Not available	13.50
0790-B-19	20	19	0.135 (0.005)	Step	0.16	3.3 (0.1)	Not available	36.00
1150	10	1	0.125 (0.005)	Graded	0.16	0.25 (0.001)	200	1.00
1156	6	1	0.125 (0.005)	Graded	0.16	0.25 (0.001)	200	0.50
1151	10	1	0.125 (0.005)	Graded	0.16	0.25 (0.001)	400	1.50
1157	6	1	0.125 (0.005)	Graded	0.16	0.25 (0.001)	400	2.00
1152	10	1	0.125 (0.005)	Graded	0.20	0.25 (0.001)	200	1.50
1158	6	1	0.125 (0.005)	Graded	0.20	0.25 (0.001)	200	2.00
1153	10	1	0.125 (0.005)	Graded	0.20	0.25 (0.001)	400	2.00
1159	6	1	0.125 (0.005)	Graded	0.20	0.25 (0.001)	400	2.50
1025	10	1	0.125 (0.005)	Step	0.18	0.25 (0.001)	20	1.00
1028	6	1	0.125 (0.005)	Step	0.18	0.25 (0.001)	20	1.50

Product Number	Attenuation, dB/m	Bundle Diameter, in. (mm)	Fiber Size	Index Profile	Numerical Aperture	Cable Outer Diameter in. (mm)	Bandwidth MHz/km	Price/ Meter
Multifiber Bundles								
5010	app 5	0.045 (1.14)	*	Step	0.63	.087 (2.21)	**	†
5011	app 5	0.062 (1.57)	*	Step	0.63	.120 (3.05)	**	†
5012	app 5	0.078 (1.98)	*	Step	0.62	.126 (3.20)	**	†
5013	app 5	0.091 (2.31)	*	Step	0.63	.139 (3.53)	**	†
5015	app 5	0.045 (1.14)	*	Step	0.63	.075 (1.91)	**	†

*Fiber size not given.

**Bandwidth not listed.

†Price by quotation only (for lengths 20 m or more).

4. Fiber Communications, Inc.
391 Lakeside Ave.
Orange, NJ 07050

Product line includes two multimode low-loss fibers (510 and 520) and a single-mode fiber. Table A3 lists the fiber characteristics.

5. Fiberoptic Cable Corp.
P. O. Box 1492
Framingham, MA 01701

Product line includes low-loss multimode fibers in the nine configurations listed in Table A4. These fibers consist of pure fused-silica core and a high temperature optical-quality plastic cladding.

Table A3
Characteristics of Fiber Communications Fibers

	Multimode Fibers	
	510	**520**
Material	All glass	All glass
Attenuation, dB/km	10 @ 800 nm	7 @ 1.06 nm
Number of Fibers	1	1
Fiber Size Outer Diameter, mm (in.)	90 or 127 (0.0036 or 0.005)	90 or 122 (0.0036 or 0.005)
Jacket Outer Diameter, mm (in.)	0.25 (0.0098)	0.25 (0.0098)
Numerical Aperture	0.16	0.16
Terminations	Cleaved flat or with stainless steel ferrules	Cleaved flat or with stainless steel ferrules
Jacket Material	Polyester	Polyester
Additional Loss Due to Jacket, dB/km	5	5
Index Profile	Step	Step
Price/Meter	$4.00	$2.25

	Single-Mode Fiber
Fiber Material	All glass
Attenuation, dB/m	0.25 @ 632.8 mm
Index Profile	Step
Numerical Aperture	0.10 to 0.12
Length, m	75 to 1000
Fiber Outer Diameter, μm (in.)	40 μm (0.0016)
Core Diameter, μm	2.5
Optional Jacket Material	Polyester
Jacket Outer Diameter, mm (in.)	0.25 (0.0098)
Fiber Termination	Cleaved flat
Price/Meter	$10.00

Table A4
Characteristics of Fiberoptic Cable Fibers

	Simplex Cable			Ruggedized Simplex Cable			Ruggedized Duplex Cable		
	Q1-1-10	Q1-7-5	Q1-7-10	Q1R-1-10	Q1R-7-5	Q1R-7-10	Q2R-1-10	Q2R-7-5	Q2R-7-10
Number of Channels	1	1	1	1	1	1	2	2	2
Number of Fibers/ Channel	1	7	7	1	7	7	1	7	7
Fiber Core Diameter, mm (in.)	0.25 (0.010)	0.125 (0.005)	0.25 (0.010)	0.25 (0.010)	0.125 (0.005)	0.25 (0.010)	0.25 (0.010)	0.125 (0.005)	0.25 (0.010)
Bundle Diameter, mm (in.)	0.25 (0.010)	0.375 (0.015)	0.75 (0.030)	0.25 (0.010)	0.375 (0.015)	0.75 (0.030)	2 × .25 (2 × .010)	2 × .375 (2 × .015)	2 × .75 (2 × .030)
Maximum Attenuation @820 mm, dB/km	20	50	40	20	50	40	20	50	40
Channel Isolation	—	—	—	—	—	—	>100 dB	>100 dB	>100 dB
Index Profile	Step	Step	Step	Step	Step	Step	Step	Step	Step
Numérical Aperture	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Acceptance Cone Full Angle	29°	29°	29°	29°	29°	29°	29°	29°	29°
Core Index of Refraction	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45
Radiation Hardness, radians	10^7	10^7	10^7	10^7	10^7	10^7	10^7	10^7	10^7
Pulse Dispersion, nsec/km	30	40	30	30	40	30	30	40	30
Maximum Continuous Cable Length, km	1	1	1	1	1	1	1	1	1
Jacket Material	Hytrel*	Hytrel*	Hytrel*	Hytrel*/ Kevlar*	Hytrel*/ Kevlar*	Hytrel*/ Kevlar*	Hytrel*/ Kevlar*	Hytrel*/ Kevlar*	Hytrel*/ Kevlar*
Outer Cable Diameter mm (in.)	2.5 (.100)	2.5 (.100)	2.5 (.100)	3.75 (.150)	3.75 (.150)	3.75 (.150)	5 × 8.75 (.20 × .35)	5 × 8.75 (.20 × .35)	5 × 8.75 (.20 × .35)
Maximum Cable Weight, kg/km	6	7.5	10.0	7	8	11	15	18.5	23.5
Temperature Range, °C	−50 to +150	−50 to +150	−50 to +150	−50 to +150	−50 to +150	−50 to +150	−50 to +150	−50 to +150	−50 to +150
Tensile Load, kg	1	1	1	23	23	23	45	45	45
Maximum Bend Radius, cm (in.)	2.5 (1.0)	3.0 (1.2)	3.5 (1.4)	2.5 (1.0)	3.0 (1.2)	3.5 (1.4)	3.0 (1.2)	3.5 (1.4)	4.0 (1.6)
Price/Meter	\$ 1.65	\$ 4.00	\$ 9.50	\$ 1.75	\$ 4.20	\$ 9.75	\$ 3.50	\$ 8.50	\$ 20.15
Minimum Order	\$ 75.00	\$100.00	\$100.00	\$100.00	\$150.00	\$150.00	\$150.00	\$200.00	\$200.00

*Trademark of DuPont Corporation.

6. Galileo Electro-Optics Corp.
   Galileo Park
   Sturbridge, MA 01518

Product line includes five categories of fibers for various communications distances as shown below:

a. Galite 1000: 1 to 37 m

b. Galite 2000: 37 to 70 m

c. Galite 3000: 70 to 330 m

d. Galite 4000: 330 to 550 m

e. Galite 5000: 550 m

In addition, standard connectors for fiber ends are offered; these connectors can include either a silicon photodiode or an LED, or hybrid transmitter or receiver modules can be in the connectors.

Galite 1000 and 2000 fibers can be supplied with either a flame-retardant PVC jacket (type P) or a high/low temperature Tefzel jacket (type T). Galite 3000, 4000, and 5000 fibers can be supplied with either of these jackets or with a multiple jacketing with strengthening members (type S).

Galite 1000 and 2000 fibers are multifiber bundles containing 212 fibers, whereas the 3000, 4000, and 5000 types can be supplied in single-fiber, seven-strand, or 19-strand configurations. Table A5 summarizes the characteristics of all five fiber categories.

7. International Fiber Optics
   (Division of IRT Corp.)
   7650 Convoy Court
   Box 80817
   San Diego, CA 92138

Product line includes polymer optical fibers with step index. These fibers use a polystyrene core with a thin cladding of methylmethacrylate and can be supplied either singly or in bundles in the form of light lines, image guides, read heads, fiber optic ribbons, etc. In addition to the line of fibers, a line of "off-the-shelf" fiber optic communications links are offered which can transmit and reconstruct analog as well as digital signals.

Bulk fibers are available in diameters of .005, .010, .020, .030, 040, .050, and .060 in. (0.127, 0.254, 0.508, .0.762, 1.016, 1.270, 1.524 mm). Other sizes can be made on special order. Table A6 summarizes the fiber characteristics.

Table A5
Characteristics of Galite Fibers

Galite Type	1000	2000	3000	4000	5000
Attenuation, dB/km	650	350	60	30	10
Number of Fibers	212	212	1, 7, 19	1, 7, 19	1, 7, 19
Fiber Size Outer Diameter, mm (in.)	0.068 (0.003)	0.068 (0.003)	0.110 (0.004)	0.125 (0.005)	0.125 (0.005)
Numerical Aperture	0.66	0.66	0.48	0.35	0.2
Bundle Diameter, mm (in.)	1.14 (0.045)	1.14 (0.045)	Not available	Not available	Not available
Price/Meter*	\$0.33 to \$1.71**	\$0.66 to \$2.20**	\$0.75 to \$4.85**	\$1.25 to \$6.17**	Not available

*For 1000-m quantities.

**Price depends on number of fibers per bundle and type of jacketing.

8. ITT
Electro-Optical Products Division
7635 Plantation Road
Box 7065
Roanoke, VA 24109

Product line includes low- and medium-loss fibers and cable. Cables can have one, six, seven, or 19 fibers. In addition to fibers, optical fiber digital terminals and optical fiber analog terminals are available on special order for making up complete communications links. The digital link is capable of 25 megabits/sec and inputs and outputs are transistor-transistor logic (TTL) compatible with an amplitude regenerated output also provided. The analog terminals have one wideband and two narrowband channels with frequency modulation (FM) multiplexing used to enable a single optical channel to carry the three analog channels. Table A7 presents the nominal characteristics of the optical fibers.

Table A6
Characteristics of International Fiber Optics Fibers

Attenuation—1.2 dB/m @ 800 mm
Numerical aperture—.58

Catalog Number	Diameter, in. (mm)	Single-Spool Price/1000 ft (/km)
50005	0.005 (0.127)	\$ 1.20 (3.94)
50010	0.010 (0.254)	2.50 (8.20)
50020	0.020 (0.508)	6.00 (19.69)
50030	0.030 (0.762)	17.00 (55.77)
50040	0.040 (1.016)	28.00 (91.86)
50050	0.050 (1.270)	60.00 (196.85)
50060	0.060 (1.524)	90.00 (295.28)

9. Valtec
Electro-Fiberoptics Division
West Boylston, MA 01583

Product line includes both a high-loss cable and low-loss cables for communications links in addition to fiber optic data links using connectors with LEDs and photodetectors. Medical fiber optics, light guides, scanners, illuminators, and other special-purpose equipment are also offered. Table A8 shows the characteristics of the optical fibers.

10. Welch Allyn, Inc.
Skaneateles Falls, NY 13153

Product line includes step-index plastic monofilament fiber optics in addition to medical fiber optics. The plastic fibers are in the high-loss classification and use an acrylic cladding and polystyrene core.

Table A7
Characteristics of ITT Fibers

Type	Material Type	Attenuation, dB/km	Numerical Aperture	Index Profile	Fiber Diameter, mm(in.)	Number of Fibers	Price/ Meter
PS-50L	Plastic-clad silica	50	0.25	Step	0.1250 (0.005)	7 or 19	\$6 to \$10*
PS-5011	Plastic-clad silica	50	0.25	Step	0.1250 (0.005)	6	Not available
GS-2011	Not available	14	0.25	Step	0.1250 (0.005)L	6	\$9 to \$12**
PS-05-40	Plastic-clad silica	40	0.25	Step	Not available	1	\$1
GS-02-10	Doped silica	8	0.25	Step	Not available	1	\$2†

*Price depends on jacket.
**Price depends on configuration.
†\$3/m for strengthened cable.

Table A8
Characteristics of Valtec Fibers

	Fiber Type	
	High-Loss	*Low-Loss*
Core Material	Flint glass	Pure fused silica
Cladding	Soda lime	Plastic
Attenuation, dB/km	400	40
Numerical Aperture	0.56	0.30
Fiber Outer Diameter, in. (mm)	0.002 (.051)	0.006 (0.152)
Bundle Diameter, in. (mm)	.015, .030, or .045 (0.381, 0.762, 1.143)	NA*
Jacket	Hytrel	Hytrel
Price	Not Available	

*Can be supplied in cables of one to 40 fibers depending on requirements.

The fiber characteristics are as follows:

Attenuation—approx. 40 percent/ft
Diameter—.002 to .325 in. (0.051 to 8.255 mm) (can be supplied in any diameter within the range)

Numerical Aperture—.58

Core/Cladding Ratio—80 percent

Jacketing—Polyethylene (available on special request)

Pricing Examples: .005 in. (0.127 mm) diameter nonjacketed at $30 for 10,000 ft (3048 m).

.030 in. (0.762 mm) diameter nonjacketed at $50 for 2,000 ft (610 m).

In addition to the U. S. companies listed above, optical fibers for communications are also manufactured by foreign companies, including the following:

11. Pilkington Bros. Ltd.
    Research and Development Laboratories
    Lathom Ormskirk, Lancashire
    L40 5 UF
    England

Information on product line is not available.

12. Rank Precision Industries, Inc.
    Representative for Rank Optics
    200 Harehills Lane
    Leeds LS8 50S
    England

Product line includes various cable configurations of a high-loss (400 dB/km) multifiber cable.

13. Schott Optical Glass, Inc.
    Representatives for:
    Jenaer Glaswerk Schott & Gen. Mainz
    Hattenbergstr. 10
    West Germany

Product line includes a 300-dB/km multifiber bundle.

14. Nippon Electric Co., Ltd.
    NEC Building
    33-1 Shiba Gochome
    Minato-ku
    Tokyo, 108, Japan

Product line includes SELFOC, a self-focusing, graded-index fiber with low-loss rating.

APPENDIX B: INTERACTION OF NUCLEAR RADIATION WITH MATTER

While the exact mechanisms of the interaction of the various types of nuclear radiation with matter is a complicated subject beyond the scope of this report, some general information is useful in interpreting the results presented in the literature. For purposes of this report, it is convenient to classify nuclear radiation into four general categories:

1. Heavy charged particles (e.g., protons [p], deuterons [d], tritons [t], and alpha particles [α])

2. Light charged particles (e.g., electrons [e] or beta particles [β])

3. Gamma rays (γ) and X-rays (X)

4. Neutrons (n).

Of the several interactions which heavy charged particles have with matter, the contribution of nuclear transmutation is negligible. The contribution of nuclear collisions is also negligible compared with that of ionization and excitation for this type of radiation. (It might be noted, however, that for fission products, the nuclear collisions are important interactions.) For the most part, the charged particles interact primarily with the Coulomb fields of the atomic electrons, resulting in excitation or ionization. Because their mass is relatively large compared with that of an electron, the path of the heavy charged particles passing through matter depends on the mass and charge of the particle. Since the ranges of heavy charged particles are comparatively short, they are not important in terms of external radiation; however, if they arise within the fiber material itself (e.g., as the result of neutron interaction), these particles can cause considerable damage.

The interactions of electrons with matter differ from those of the heavy charged particles in that they are not characterized by the straightline pattern and definite ranges associated with the heavy charged particles. This is due to collision with the atomic electrons or with the nuclei of the absorbing material. Energetic electrons (beta particles if they are of nuclear origin) interact with matter principally by the following processes:

1. Elastic collision.

2. Inelastic collision (excitation and ionization). The electrons which are released in the primary ionization process are often given large energies and produce additional (secondary) ionization while dissipating the energy.

3. Bremsstrahluing (braking radiation). According to classical electromagnetic theory, when electrons are accelerated, as the result of an inelastic collision, they radiate energy in the form of continuous X-ray emission.

Gamma rays and X-rays differ only in their origins. Gamma rays result from nuclear reactions, whereas X-rays originate in interactions with atomic electrons. Gamma rays and X-rays interact with matter primarily through three mechanisms:

1. Photoelectric effect. In the photoelectric effect, a photon interacts with an atom to transfer all of its energy to an electron, usually one in the innermost shell. In the process, the photon disappears and the electron is ejected from the atom with kinetic energy equal to the gamma energy minus the binding energy. When the outer shell electrons fill the lower energy levels, one or more characteristic X-rays are emitted, with the total energy being equal to the binding energy.

2. Compton effect. The Compton effect can be considered as an elastic collision between the gamma ray photon and an individual orbital electron. After the collision with the primary photon, the recoil electron (referred to as a Compton electron) and the scattered photon (a secondary photon with lower energy) move off in such a manner as to conserve energy and momentum. The Compton scattering results in a change of direction of the photon and a reduction in its energy. The gamma energy is reduced by such scatterings, and eventually the photoelectric effect takes place. The Compton effect becomes important for gamma energies of about 0.1 MeV and up.

3. Pair production. In pair production, there is complete absorption of the primary photon in the vicinity of a nucleus and the production of a positron-electron pair. Since a positron-electron pair has a rest mass of $2\ m_0c^2$ (1.022 MeV), where m_0 is the electron rest mass and c is the speed of light, the primary photon must have at least this energy, with any excess energy going into the kinetic energy of the positron and electron. Eventually, the positron undergoes annihilation with a negative electron; both particles then disappear and their mass is converted into the energy of a pair of 0.51 MeV photons.

The interaction of neutrons with matter is quite different from either charged particles or gamma rays. Since neutrons are uncharged, they interact with nuclear forces rather than Coulombic forces of either the orbital electrons or nuclei; in contrast, nuclear reactions play only a minor part in the interaction of charged particles and gamma rays with matter. The reaction of a neutron with a nucleus results in the formation of a compound nucleus in an excited state. The excitation energy of the neutron (including the kinetic and binding energy) is distributed among the various constituents of the nucleus. The compound nucleus remains in the excited state for a short time; the excess energy may then be emitted by any of several nucleus reactions, the probabilities of which depend on the amount of excitation energy and the location of energy levels in the compound and product nuclei. Consequently, the probability for each type of absorption process depends

on the energy of the incident neutron and the composition of the material. Since the interaction of neutrons with matter depends on their energy, neutrons are usually classified according to their energies as being thermal, epithermal, or fast. These terms represent broad rather indefinite ranges of neutron energies. Thermal neutrons are those which slow down to thermal equilibrium with their surroundings. They have roughly a Maxwellian distribution of velocities. At room temperature (20°C), the thermal neutrons have an average kinetic energy of 0.038 eV, which corresponds to a neutron velocity of 2200 m/sec.

Epithermal neutrons are those which are between thermal and fast. The lower limit on the fast neutron groups is more or less arbitrary, but is often taken to be about 100 keV.

There are several mechanisms by which neutrons interact with matter:

1. Elastic scattering (n,n).* Processes in which neutrons are reemitted are referred to as scattering processes. Scattering is classified as inelastic or elastic depending on whether the nucleus is left in an excited or unexcited state after the neutron emission.

In the elastic collision, there is a simple transfer of kinetic energy from the neutron to the nucleus without exciting it, so that this type of interaction is not accompanied by gamma radiation. Elastic scattering can occur with neutrons of all energies and any nucleus. The smaller the nucleus, the greater the fraction of energy it can receive. Theoretically, the entire kinetic energy of a neutron could be transferred to a hydrogen nucleus (proton) in a single head-on collision.

2. Inelastic collision (n,n), (n,nγ), or (n,2n). In this case, a neutron interacts with a nucleus and transfers some of its kinetic energy to the nucleus leaving it in an excited state. This interaction is energetically possible only for fast neutrons. In the (n,nγ) reaction, the nucleus returns to its ground state by emission of a gamma ray. In the (n,n) reaction, the nucleus remains in a metastable state. The (n,2n) process can occur for neutrons with incident energy of 10 MeV or higher.

*It is customary to abbreviate the nuclear reaction in the form (a,b), where a represents the incoming particle and b represents the outgoing product.

3. Radiative capture or simple capture (n,γ). In this reaction, the compound nucleus achieves stability by emission of gamma radiation called **capture gamma rays**. This reaction is more probable with thermal and epithermal neutrons. It is probably the most common of all reactions, since thermal neutrons induce this reaction in nearly all nuclides.

4. Charged particle ejection (n,p), (n,d), (n,t), (n,α), etc. In this type of reaction, a neutron is absorbed and a charged particle ejected (e.g., proton, deuteron, triton, or alpha particle). The residual nucleus is often in an excited state and emits the excess energy as gamma radiation. One interaction of particule note is

$$B^{10} + n^1 \rightarrow Li^7 + \alpha$$

5. Fission (n,f). In a fission reaction, a neutron is absorbed and its compound nucleus splits into two fission fragments and one or more neutrons. This interaction is restricted to a small number of nucleus species. Fission occurs with thermal neutrons in U^{235} and with fast neutrons in several heavy nuclides.

It should be noted that the cross section (the probability of a particular type of interaction occurring) depends on the energy of the neutron, often in a very complicated manner, as well as the type of target nucleus.

While it is not essential for the scope of this report to describe the exact mechanisms by which these interactions of nuclear radiation with matter interfere with the normal operation of optical fiber communication systems, it is important to realize that nuclear radiation can and does interact with optical fibers.

APPENDIX C: ADDITIONAL ORGANIZATIONS PERFORMING OR RESPONSIBLE FOR DOD-SPONSORED R&D

Government agencies (in addition to those mentioned in the text) either responsible for or performing DOD-sponsored R&D are:

1. Advanced Research Projects Agency

2. Air Force Avionics Laboratory

3. Air Force Cambridge Research Laboratories
4. Air Force Office of Scientific Research
5. Air Force Weapons Laboratory
6. Defense Communications Agency
7. Defense Nuclear Agency
8. Energy Research and Development Agency
9. Jet Propulsion Laboratory
10. National Aeronautics and Space Administration
11. National Security Agency
12. Naval Air Development Center
13. Naval Air Systems Command
14. Naval Avionics Facility, Indianapolis
15. Naval Electronic Systems Command
16. Naval Material Command
17. Naval Oceanographic Office
18. Naval Sea Systems Command
19. Naval Undersea Center
20. Naval Underwater Systems Center
21. Naval Weapons Center
22. North American Air Defense Command
23. Office of Naval Research
24. Rome Air Development Center
25. U. S. Army Materiel Development and Readiness Command
26. U. S. Army Missile Command
27. U. S. Army Office of Chief of Engineers

Corporations (other than fiber manufacturers) and universities doing DOD-sponsored research and/or development work in fiber optics are:

1. Air Logistics Corp.
2. Arthur D. Little, Inc.
3. Battelle Columbus Laboratories
4. California Institute of Technology
5. California University
6. Carnegie-Mellon University
7. Catholic University of America
8. David Sarnoff Research Center
9. GTE Laboratories, Inc.
10. Harris Intertype Corp.
11. Hughes Aircraft Co.
12. IBM Corp.
13. IRT Corp.
14. Litton Industries, Inc.
15. Litton Systems, Inc.
16. LTV Aerospace Corp.
17. Northrop Corp. Laboratories
18. Opticom
19. Polytechnic Institute of New York
20. RCA Research Laboratories
21. Rhode Island University
22. Spectronics, Inc.
23. Texas Instruments, Inc.
24. Titra Tech Inc.
25. TRW Systems
26. University of California at Los Angeles
27. University of Illinois

28. University of Michigan

29. University of Texas

30. University of Utah

31. University of Washington

32. Vought Systems Div (LTV)

33. Washington University, St. Louis

34. Yeshiva University

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